

# Nonhydrostatic Hindcasts of High Amplitude Internal Waves in the Mid-Atlantic Bight

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**Abstract-** From late July to early September 2006 an intense field program, Shallow Water 2006 (SW06), was conducted in the Mid-Atlantic Bight (MAB) off of the New Jersey coast. The goal of the program is to determine the environmental processes that affect shallow water acoustic propagation and scattering and to understand the dynamics of the generation and evolution of those processes. A phenomena that dominates much of the hydrodynamics in the coastal ocean are the internal waves. The waves interact with each other, with the topography and with the ambient currents and stratification to form a complex field of baroclinic internal waves of varying frequencies and wavelengths. Many of these waves are nonlinear and have very high amplitudes (exceeding 50m) hence large energy. The generation, interactions and transformations of these waves is studied with a very high resolution, nonhydrostatic (NRL-MIT) model system of the ocean hydrodynamics. This model is imbedded in a nested hydrodynamic nowcast/forecast system comprised of the global Navy Coastal Ocean Model (NCOM) and a series of higher resolution NCOM domains.

## I. INTRODUCTION

Much of the hydrodynamics in the coastal ocean are dominated by internal waves. These waves are generated by barotropic tides interacting with topography and with the internal stratification in the ocean, by meanders and eddies from the Gulf Stream and by atmospheric forcing. The waves interact with each other, with the topography and with the ambient currents and stratification to form a complex field of baroclinic internal waves of varying frequencies and wavelengths. Many of these waves are nonlinear and have very large amplitudes hence high energy levels.

These nonlinear internal waves (NLIWs) are being studied using the in-situ and remote sensing measurements from the Shallow Water Experiment 2006 (SW06) and models of the ocean hydrodynamics. The purpose of SW06 was to understand the environment and the environmental uncertainties that impact acoustic propagation and scattering in coastal waters (depths of 20m to 200m). This includes the 4D water column variability as well as the bottom characteristics. SW06 was a very large field program involving over 50 scientists from more than 20 institutions. The project was funded by the Office of Naval Research through three programs: the Littoral Environmental Acoustics Research (LEAR) program, the Non-Linear Internal Wave Initiative (NLIWI) program and the Autonomous Wide Aperture Cluster for Surveillance (AWACS) program.

Section II of this paper presents a brief description of the hindcast and forecast systems. Section III describes the numerical experiments. Section IV discusses the results and Section V summarizes the results and provides conclusions.

## II. THE MODELING SYSTEMS

The Modeling Systems consists of the NRL-MIT model system and the Navy Coastal Ocean Model (NCOM) nowcast/forecast system. The NCOM system includes several mesoscale NCOM domains nested inside regional NCOM domains which, in turn, are nested in the Global NCOM. A submesoscale domain of the NRL-MIT model system is imbedded inside the highest resolution mesoscale NCOM domain, then higher resolution NRL-MIT model system domains are sequentially imbedded until the desired resolution is obtained. This "Russian Doll" approach allows for very high resolution modeling. We have successfully

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 30-01-2008		2. REPORT TYPE Conference Proceeding		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Nonhydrostatic Hindcasts of High Amplitude Internal Waves in the Mid-Atlantic Bight			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 060274N		
6. AUTHOR(S) Patrick C. Gallacher, Michael Schaferkotter, William E. Avera			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER 73-M140-A7-5		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory Oceanography Division Stennis Space Center, MS 39529-5004			8. PERFORMING ORGANIZATION REPORT NUMBER NRL/PP/7330-07-7261		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 N. Quincy St. Arlington, VA 22217-5660			10. SPONSOR/MONITOR'S ACRONYM(S) ONR		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
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15. SUBJECT TERMS NCOM, Mid-Atlantic Bight, internal waves, hindcast					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UL	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON Patrick Gallacher
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 228-688-5315



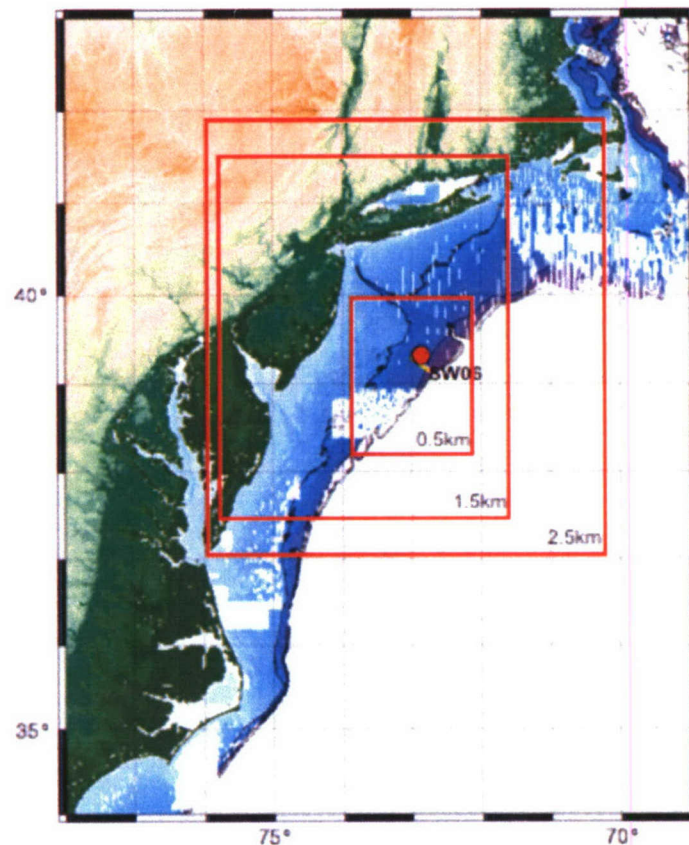
conducted simulations at resolutions of 1m and timesteps of less than 1 s to study individual internal bores. The only limitations are available computer time and the quantity of data that can be stored, moved, and analyzed.

At NRL the MITgcm nonhydrostatic ocean model is being used to hindcast the submesoscale dynamics in several regions including the Mid-Atlantic Bight (MAB). The model is forced by open boundary conditions with values prescribed by data from the NCOM forecasts or hindcasts as described above. The MITgcm model is fully nonhydrostatic [1]. It supports horizontal orthogonal curvilinear coordinates and has a finite volume treatment of topography [2]. The model uses a flexible domain decomposition method for parallel processing. We typically use the model at DOD High Performance Computer (HPC) Major Shared Resource Centers (MSRCs) using hundreds of processors.

The NCOM nowcast/forecast system is composed of a series of hydrostatic models. These models are forced at the open boundaries with  $u$ ,  $v$ ,  $T$  and  $S$  from the near-real-time global NCOM forecasting system [3] and [4] and surface fluxes from the COAMPS Northwestern Atlantic operational forecast system [5]. Equilibrium tides are obtained from the OSU (Egbert) global tidal database [6] and [7]. Ten constituents are included: K1, O1, P1, Q1, M2, S2, N2, K2, MF, MM. This includes both height and velocity values of the tides. The bathymetry used for the system is the NRL DBDB2 (2 minute) bathymetry which is based on the NAVO global 5-min DBDBV bathymetry and is enhanced with other higher resolution bathymetries and coastlines.

### III. NUMERICAL EXPERIMENT

A simulation system is being developed for the MAB consisting of multiply nested NCOM models with increasing resolution then the NRL-MIT model system(s) are forced by the highest resolution NCOM domain. The results described here are from a system consisting of three nested NCOM models with increasing resolution (approximately 2.5 km, 1.5 km and 0.5 km) (Fig. 1). The nested NCOM system is forced with global ( $1/8^\circ$ ) NCOM fields and atmospheric fluxes as described above.



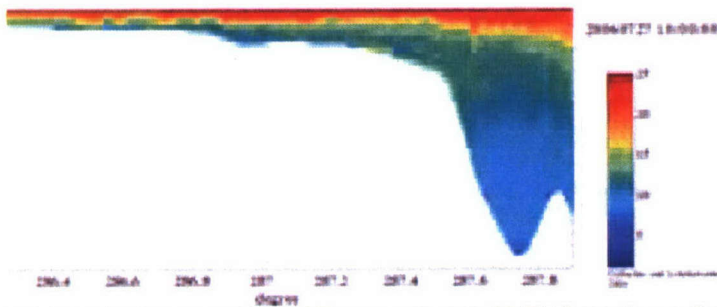
**Figure 1** The three NCOM nests are indicated by the red boxes. The resolution of the nests are 2.5km, 1.5km and 0.5km. SW06 marks the approximate position of the center of the experiment.

#### IV. RESULTS AND DISCUSSION

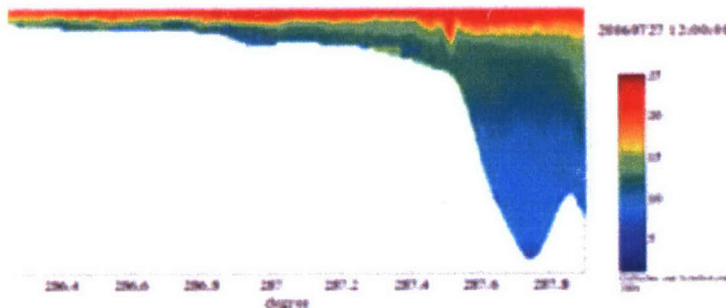
The results discussed here are from a hindcast for the period from July 25 to August 4, 2006. This covered a period during the middle of the SW06 experiment. The NRL-MIT domain consisted of a spherical polar grid with 284 points in longitude from 73.8W to 72.1W and 380 points in latitude from 38.25N to 40.0N. There were 47 points in the vertical with variable spacing from  $dz = 1.0$  m at the surface to  $dz = 300.0$  m at the bottom. The time step was 15.0 s and the forcing at the boundaries was interpolated from hourly data from the 0.5 km NCOM domain. For these initial results the NRL-MIT domain was the same as the inner most NCOM domain and with the same (500 m) resolution.

In the MAB NLIWs are typically produced locally by the breakdown of barotropic tides caused by interactions with topography and/or stratification. The barotropic tides breakdown into baroclinic tides which disintegrate into higher frequency, shorter wavelength internal waves. Unless the forcing is weak these internal waves will be large amplitude, nonlinear internal waves and bores which are ubiquitous in coastal regions, straits and other areas where there are strong topographic interactions. This process of tidal internal waves becoming bores and then transforming into solitary wave trains was seen several times during SW06 in the moored observations (Nash and Duda, personal communication) and the NLIWs were tracked by ship (Moum, personal communication). In the moored observations the NLIWs apparently were formed from baroclinic internal tides during the neap tidal cycle when the barotropic tides were weak (Nash, personal communication). This is unusual since, as stated above, the process generally starts with the barotropic tide. This will be investigated further in subsequent publications. For the present we want to examine the formation and transformation of the NLIWs.

A vertical cross section through the NRL-MIT model data during July 27<sup>th</sup> at 39.5N show the transformation of a baroclinic internal tide into an internal bore and finally into a solitary wave train (Fig 2 through Fig 4). In Fig. 2 a baroclinic internal tide is beginning to steepen into an internal bore as it encounters the start of the outer shelf. In Fig 3 an internal bore is forming as the baroclinic internal tide encounters the outer shelf.



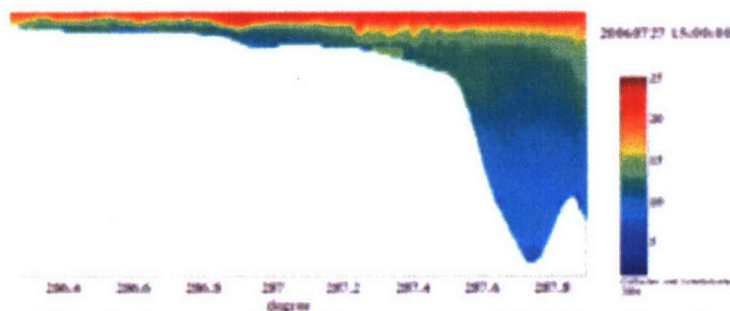
**Figure 2 . Vertical cross section of Temperature at 39.5N from the surface to 450m depth. A baroclinic internal tide is steepening east of 287E**



**Figure 3. Vertical cross section of Temperature at 39.5N from the surface to 450m depth. An internal bore is forming as the baroclinic internal tide encounters the start of the outer shelf.**

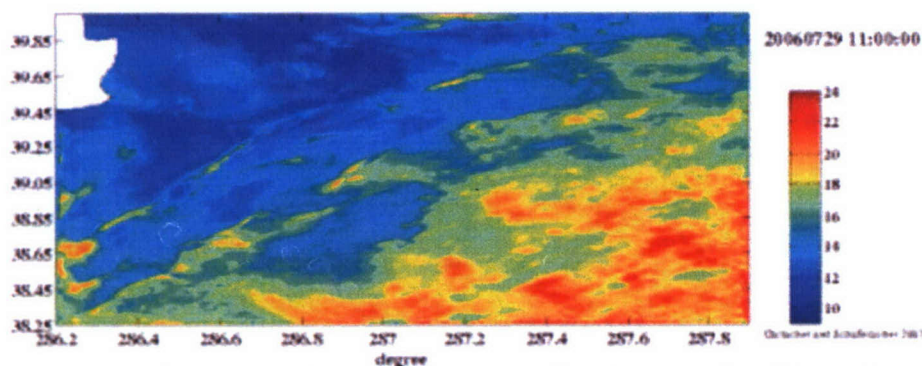
In Fig4 the internal bore breaks down into a solitary wave train as the depth decreases on the outer shelf.





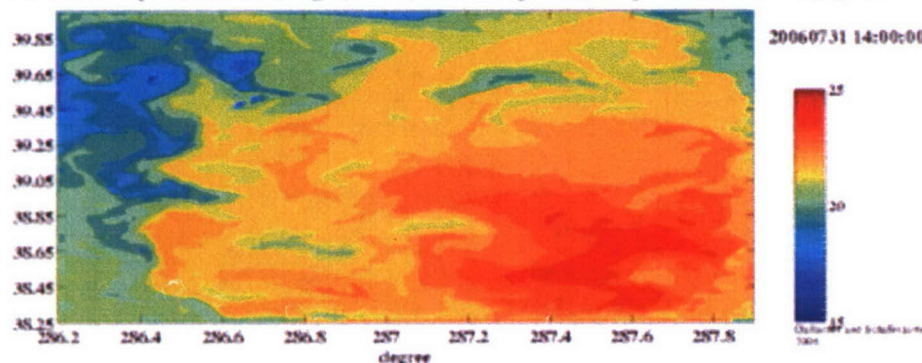
**Figure 4. Vertical cross section of Temperature at 39.5N from the surface to 450m depth. An internal bore breaks down into a solitary wave train as the depth decreases on the outer shelf.**

Horizontal cross sections show significant variations with depth. At 30 m, roughly the depth of the base of the thermocline, the generation and transformation of internal waves can clearly be seen (Fig. 5). The internal waves are generated at sites in the SE corner of this plan view. The waves start to coalesce roughly half way across the domain and form linear wave fronts in the southern and central portions of the domain. This in agreement with observations taken during SW06 and earlier experiments. In the northern part of the domain the wave fronts are more curved. This as been observed in this region which is in the vicinity of the deep part of the Hudson canyon.



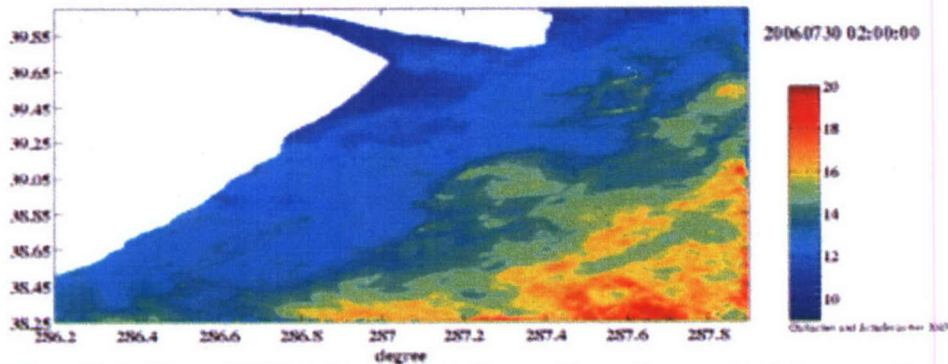
**Figure 5. At 30 m, roughly the base of the thermocline, the generation of internal waves in the SE corner of the domain can be clearly seen. Halfway across the domain the waves are coalescing into linear patterns in most of the domain except in the NE region where they are curved.**

At the surface there are indications of possible mesoscale features, such as remnants of Gulf Stream eddies that have move west and interacted with the slope or possibly inertial eddies generated by the wind (Fig 6).



**Figure 6. Temperature at the surface. Mesoscale patterns are evident which may be remnants of Gulf Stream eddies or wind-generated inertial oscillations.**

These are larger scale features with definite rotation in the animations. Below the thermocline, at 60 m, there is some evidence of submesoscale activity. There are some meandering and rotating features with distinctly smaller size (Fig 7) than the surface features in Fig. 6. In particular there is an interesting closed cell feature NE of the Hudson canyon at this depth. There is also a cold, rotating feature at the mouth of the canyon that could be a submesoscale eddy. It is seen more clearly in the animations.



**Figure 7. At 60 m, which is below the main thermocline, submesoscale features can be seen particularly in the vicinity of the Hudson canyon in the northern part of the domain.**

## V. CONCLUSIONS

We conducted a series of hindcasts using NRL-MIT nonhydrostatic model system that was forced by data generated from a multiply nested hydrostatic NCOM nowcast/forecast system. The hindcasts were for a period (July 25 – August 4) during the SW06 experiment in the MAB off the New Jersey coast. Although the hindcasts have coarse resolution (approximately 500m), the generation, interactions and transformations of barotropic and baroclinic internal tides into internal bores and nonlinear internal waves is clearly seen in the results. Barotropic and baroclinic tides were present in the forced boundary conditions as well as mesoscale activity from the Gulf Stream and wind driven circulations. Internal waves were generated in the domain, particularly at sites in the SE sector. These internal waves interacted with topographic features and generated internal bores and nonlinear internal waves. These further disintegrated into solitary wave trains as they propagated up the shelf. The waves coalesced into large scale linear wave fronts except in the NE quadrant where the large scale wave fronts were clearly more circular. This is thought to be the result of interactions with the Hudson canyon.

At the surface there was evidence of remnants of mesoscale features, possibly Gulf Stream eddies or rings that propagated up the slope. These could also be inertial oscillations generated by the wind. Below the main thermocline submesoscale features were present. These are possibly the result of mesoscale features and internal waves interacting with topography or dissipating.

## ACKNOWLEDGMENT

This work was supported by the Naval Research Laboratory through the project Effects of Non-Acoustic Noise on Multi-Sensor ASW systems (Task Area UW-435-018) and by the Office of Naval Research through the NLIWI DRI (Funding Document No. N0001407WX21138) and through Dr. Dana Hesse of the Magnetics Program (Funding Document No. N0001406WX21318). The numerical experiments were done on the DoD High Performance Computers (HPC) at the Naval Oceanographic Office Major Shared Resource Center (NAVO MSRC). The NCOM fields were provided by Dr. Germana Peggion, Dr. Clark Rowley and Ms. Lucy Smedstad.

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